

Senior Thesis

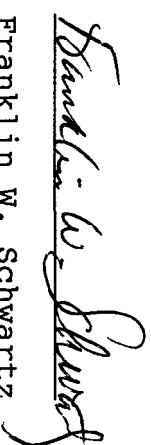
A CASE STUDY IN SMALL-BODY AQUIFER TESTING

Submitted as Partial Fulfillment of the  
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Science in the Department of Geological Sciences  
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by

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## Abstract

Determination of aquifer characteristics for small bodies requires careful evaluation of local geology. Many assumptions inherent in the use of the Theis equation and its variations may be violated. Limited areal extent, leakage, local heterogeneities, and the effects of dewatering may skew results. Results from a variety of analyses will illustrate these effects, and aid in proper evaluation of hydrologic properties.

This study undertakes such an analysis. Various methods are used to determine transmissivity and storativity in a channel sand aquifer. These include time-drawdown, distance-drawdown, type curve matching, time recovery, and image well analyses. Values of transmissivity range from 3306 to 15,500 gpd/ft, and storativity ranges from 0.0009 to 0.005. Evaluation of the limits of each method in small-body analysis indicates that actual transmissivity ranges from 10,000 to 15,000 gpd/ft, and storativity is on the order of  $10^{-4}$ .

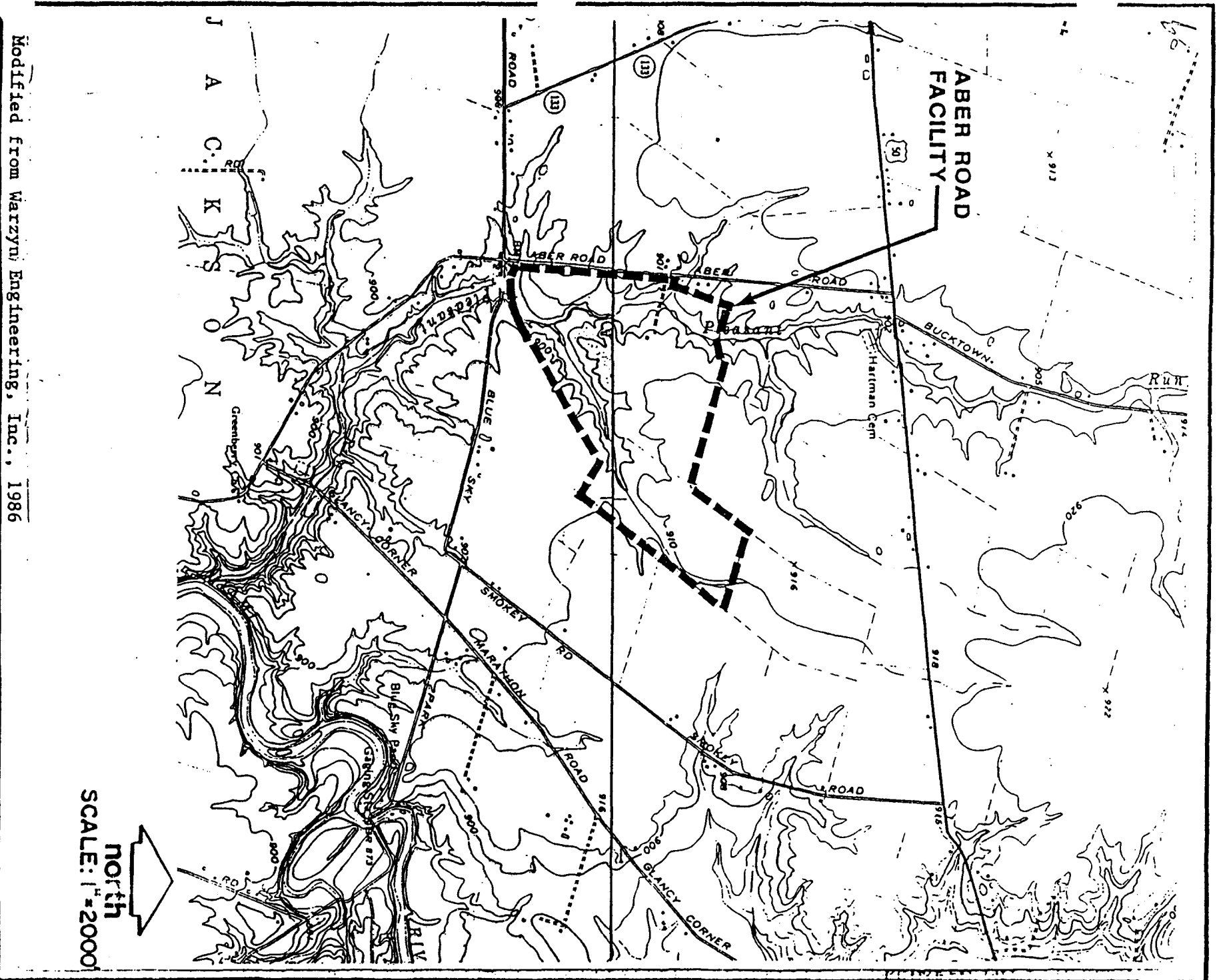
## Introduction

This paper is an evaluation of aquifer test data generated by Ground Water Associates, Inc. (GWA). The test was performed in March 1987 at the CECOS Secure Chemical Management Facility in Clermont County, Ohio (Figure 1).

The CECOS site includes 208 acres, and contains 11 disposal sites (Lawhon, 1991): a 19-acre closed sanitary landfill, an intermediate bulk disposal cell, two unlined industrial disposal cells, and seven closed secure chemical management units (SCMF'S) containing hazardous waste. During construction of SCMF No. 11, a sand body, subsequently known as the Channel Sand, was discovered. Dewatering of the Sand produced more water than expected, indicating the need for additional hydrogeologic studies.

This evaluation included a drawdown/recovery test performed with well 13-PW, in the southeast corner of the facility. The data generated by the test are extensive, and include detailed time-drawdown and time-recovery numbers from automatic instruments. These data are analysed here using five methods: time-drawdown, distance-drawdown, type curve matching, time-recovery, and image well analysis.

Results of the analyses varied significantly. Transmissivity values ranged from 3306 to 15,500 gpd/ft, and storativities varied from 0.0009 to 0.005. These variances are traceable to hydrogeologic properties of the aquifer and resulting violations of assumptions made in implementing some of the analyses. In



particular, transmissivity can be lowered, and storativity raised, by these inconsistencies.

This report examines the geological setting of the CECOS site, and evaluates the impact of geology on local groundwater flow. Following this is a description of the 13-PW drawdown/recovery test, with results of the GWA analysis. The study then proceeds with a detailed description of each of the analyses carried out for this report. This is followed by an interpretation of the results, based on the limits of each analysis.

## Location, Climate, and Regional Geology

The CECOS facility is located in Jackson Township, Clermont County, Ohio, 35 miles east of Cincinnati. The site is bordered by Pleasant Run Creek to the west, and the East Branch of Pleasant Run Creek to the east, and covers over 1000 acres.

Surface topography is level to slightly rolling. The geology regionally consists of interbedded Illinoian glacial till and sand deposits, overlying limestone and calcareous shale. The sand bodies within the till are comprised of silty sand and gravel.

The climate is characterized as humid continental. The area receives about 41 inches of annual precipitation; less than 25 inches of this is snowfall. Average annual temperature is 54 degrees Fahrenheit.

The CECOS site lies in the Clermont lobe of the Illinoian Till Plain. Glacial ice advanced from the northwest, with the presence of two tills indicating two stages of advance. The tills are generally dense clayey silts to silty clays, with varying amounts of sand and gravel (PCR, 1989). The subsurface geology at the site has been characterized by several studies (Warzyn, 1986; S&ME 1986; GWA 1987). The local stratigraphy consists of the following informal units:

- Upper Till (with the Upper Sand)
- 880 Zone (with the 880 Sand)
- Lower Till (with the Channel Sand, 840 Sand,  
and Lower Sands)
- Bedrock (with the Bedrock Till Interface (BTI))

The Upper Till extends from near the surface to between 870 and 890 feet above mean sea level (MSL). This till grades with depth from a silty clay to a sandy clay to a silty sandy clay with gravel. Hydraulic conductivity is low, averaging  $3 \times 10^{-7}$  feet per second. The Upper Till contains a discontinuous sand layer known as the Upper Sand. The Sand is typically found above 890 feet MSL, and consists of fine to medium sand with some silt. The Upper Sand is up to 10 feet thick in the northeast corner of the site.

The 880 Sand is an irregular braided stream deposit, consisting of sand and gravel, within the 880 Zone. The 880 Sand occurs between 870 and 890 feet MSL, and averages 2 feet in thickness. The Sand is laterally extensive, but is very irregular, and is absent in many locations.

Underlying the 880 Zone is the Lower Till. This silt and clay till contains sand and gravel. The mean hydraulic conductivity is  $5.6 \times 10^{-10}$  ft/sec. The Lower Till contains three sand deposits: the Channel Sand, the 840 Sand, and the Lower Sands. The Channel Sand was probably deposited very close to the ice during a period of minor glacial retreat. Hydraulic conductivity is reported as  $4.3 \times 10^{-4}$  ft/sec. The 840 Sand is restricted to a small area south and east of SCMF #11. The Lower Sands are minor discontinuous sand lenses.

#### Site Hydrogeology

Lawhorn (1992) notes that the following hydrostratigraphic units have been defined at the site:



Upper Sand

880 Zone Sand

Channel Sand

840 Sand

Lower Sands

Bedrock-Till Interface (BTI)

Of these, the 840 Sand and the Lower Sands are considered to be of minor hydrogeologic importance, and will not be discussed further.

The Upper Sand is composed of discontinuous, fine-grained sand lenses that are typically less than 1 foot thick. Ground water flow is vertically downward toward the 880 Zone Sand, which has a lower hydraulic head. Linear flow velocity is limited to 0.01 to 0.1 feet per day by the low conductivity of the Upper Till.

Flow in the 880 Zone Sand is influenced by natural and artificial factors. Site operations such as cell construction and dewatering activities have altered natural northeasterly flow. At present, flow is variable and irregular. Slug tests have indicated a conductivity value of  $3 \times 10^{-4}$  ft/sec; linear velocity is less than 1 foot per day.

The Channel Sand (Figure 2) is a significant hydrogeologic unit. It is well defined and continuous across the site. Due to dewatering at SCMF #11, flow is to the north; natural flow is to the south, with a linear velocity of less than 1 foot per day.

The Channel Sand was discovered during construction of SCMF #11 in the Summer of 1985. In the Spring of 1986, a 41-well

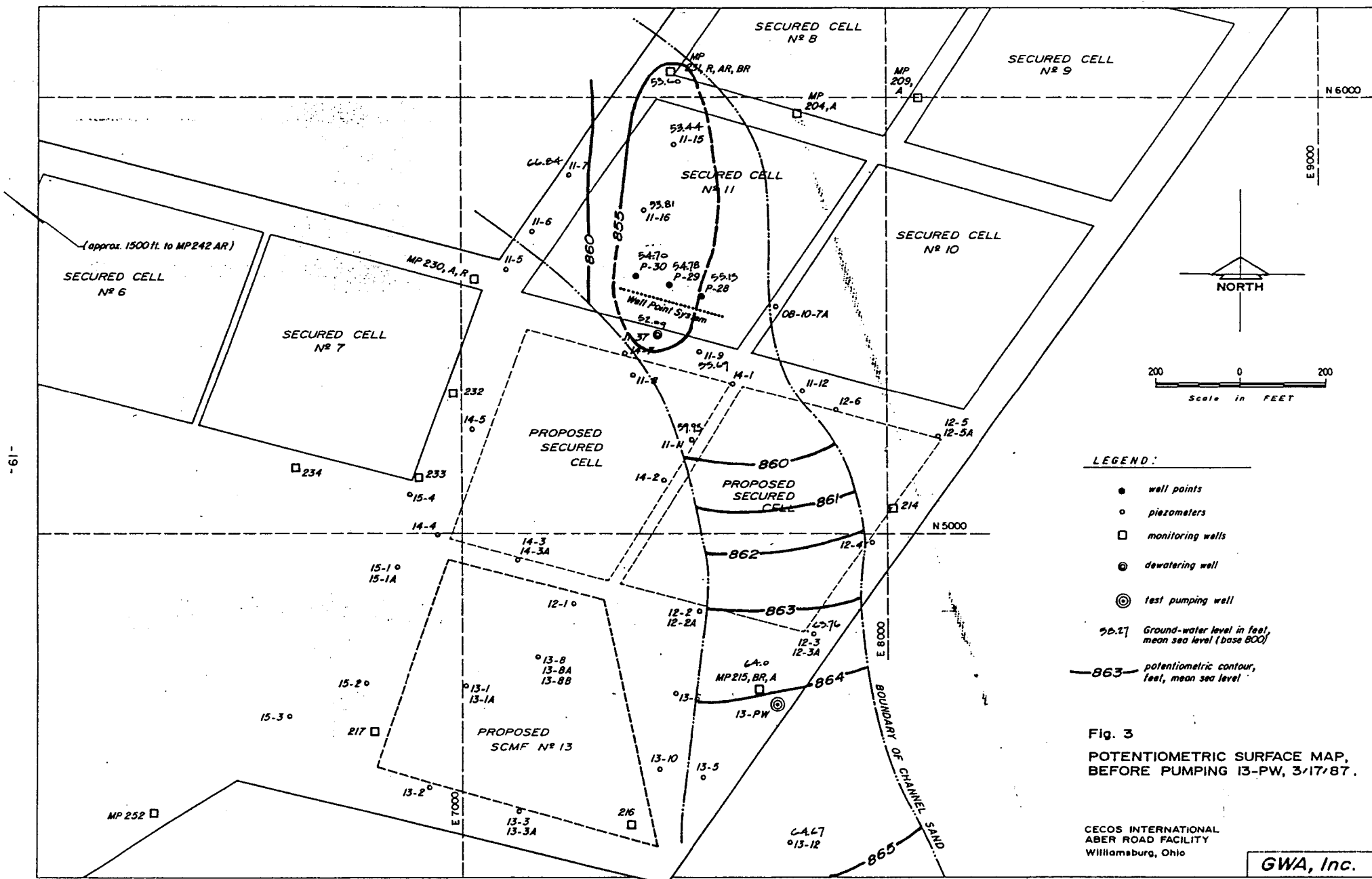
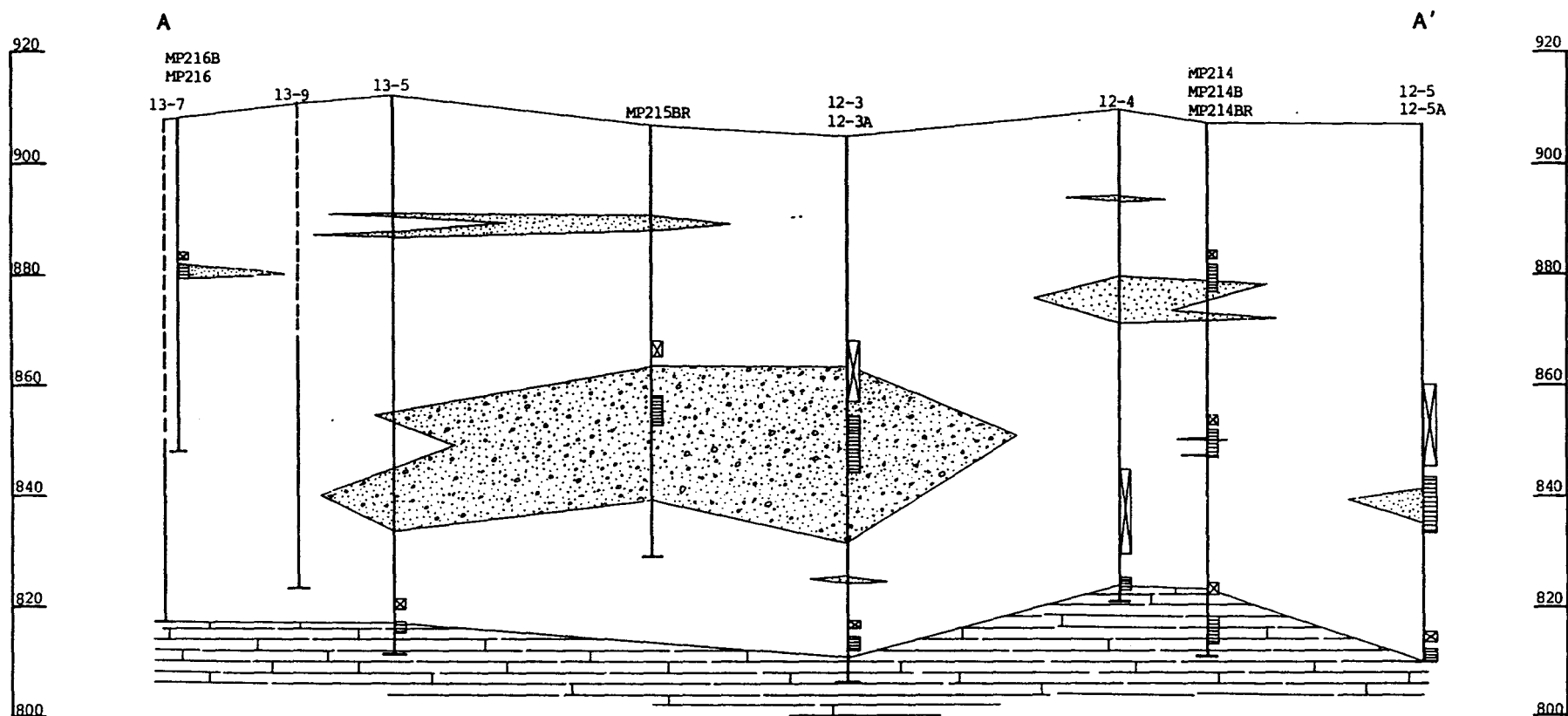


Figure 2. Plan View of Channel Sand. From GWA, 1987.

dewatering system was installed, and the cell was completed to design elevation. Subsequently, a 27-point dewatering system was installed along the southern edge of cell 11 (Figure 2). After discharge stabilized at 75-80 gallons per minute, the need for a detailed assessment of the Channel Sand became clear.

The last hydrostratigraphic unit of interest is the Bedrock-Till Interface. Most of the bedrock is overlain by low permeability till, and wells completed there are easily bailed dry. Local granular deposits are more productive, but, as a whole, the BTI is not of great hydrologic importance.

The hydrostratigraphic units noted above are hydrologically isolated by intervening till layers (Figure 3). In particular, aquifer testing showed that the Channel Sand was isolated from the other units (GWA, 1986). It has been estimated that, under pumping conditions of 100 gpm, 90% of recharge is from underflow in the Channel itself, and 10% is from the 880 Sand and the BTI. Under non-pumping conditions, the potential leakage from the 880 Sand and the BTI drops to 1/25th of that amount.



- Till
- Sand and Gravel
- Bedrock
- Screen
- Bentonite Seal
- Augered without Sampling

NOTES:

1. Geological cross sections are general in nature and do not purport to be an exact representation of subsurface conditions between borings.
2. At well location MP215 stratigraphy is from MP215B and screen elevation is from MP215BR.

Channel Sand

SOIL & MATERIAL ENGINEERS, INC.		
CINCINNATI, OHIO		
SCALE: H; 1" = 200'	DRAWN BY:	APPROVED BY:
DATE:	PROJECT NO.: 1221-87-136-1.3	
Geologic Cross Section A-A'		
CROCOS International		FIGURE: 5

Figure 3. Geologic Cross Section. S&ME, 1987.

## The 13-PW Pump Test

The source of data and the object of study of this paper is a drawdown/recovery test performed by Soil and Material Engineers, Inc. and Ground Water Associates, Inc. in March 1987. The pumping well (13-PW) and 14 of the 67 monitoring wells were screened in the Channel Sand. Well levels were recorded using Stevens Type F automatic recorders, electric tape, and by the Hydrologic Analysis System manufactured by In Situ, Inc. Figure 4 provides an example of the type of data generated by the In Situ digital data acquisition system.

The aquifer test began a 1730 hours on March 17, 1987, at an initial pumping rate of 75 gpm. At 1422 hours on the 19th, the rate was increased to 150 gpm, and to 174 gpm at 1502 hours. The rate was increased to maximize drawdown, and to increase head differences to test for possible hydraulic communication with other sand zones. Pumping was stopped at 1733 hours on March 20, and recovery readings were taken until March 22.

GWA constructed graphical analyses of time-drawdown, distance-drawdown, and time-recovery data for wells 12-3A, 13-12, 13-PW, and MP-215-BR. Transmissivity was calculated as 10,000 - 20,000 gpd/ft from time-drawdown analysis, 15,000 gpd/ft from time-recovery analysis, and 10,000 to 30,000 gpd/ft from distance-drawdown data. Storativity was determined to be on the order of 10<sup>-4</sup>, from time-drawdown analysis.

The object of this paper is to re-interpret the raw data generated by the 13-PW test. Five methods of analysis are used:

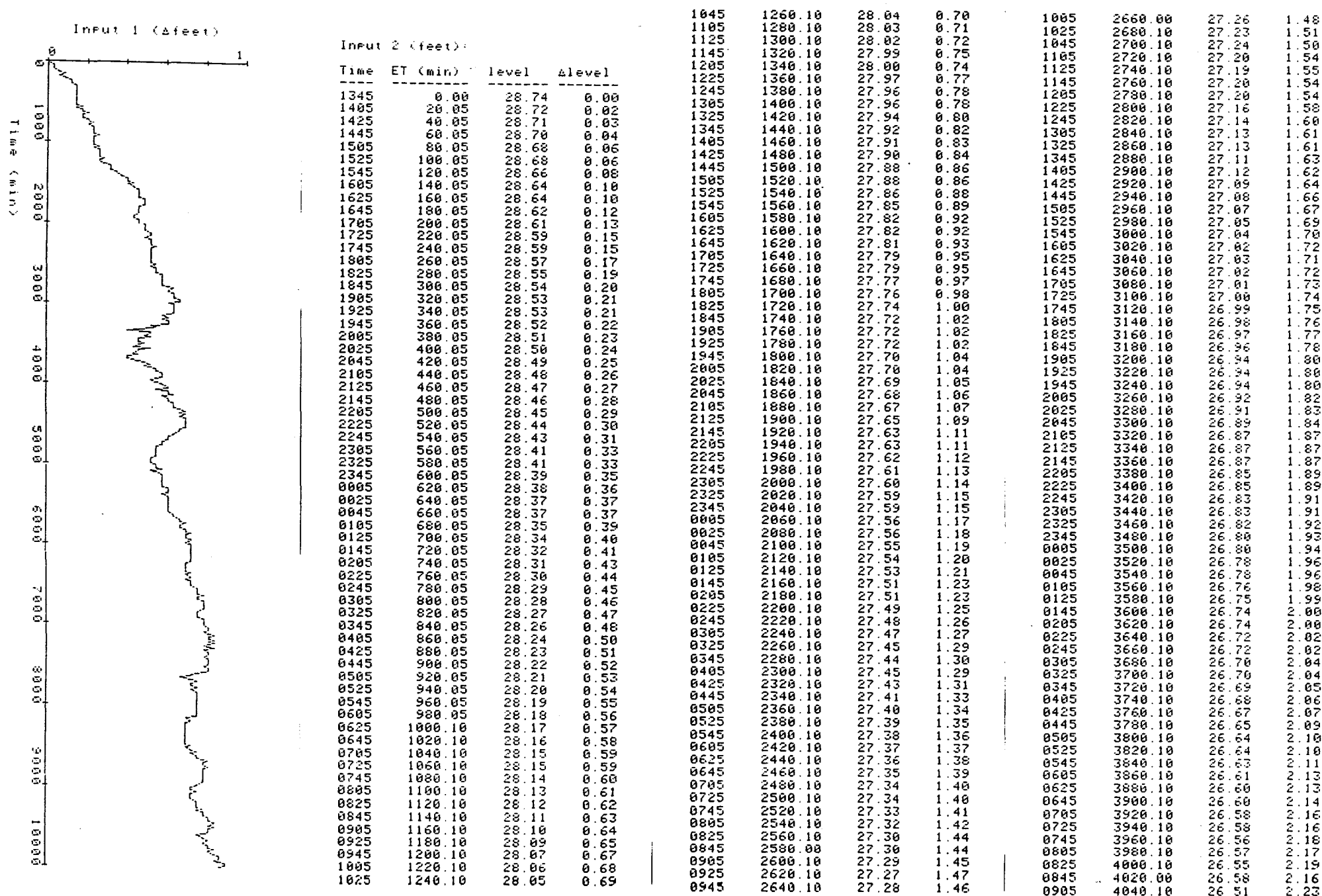


Figure 4. Sample of In Situ Data. From GWA, 1987.

Time-drawdown (log cycle time)

Distance-drawdown (log cycle distance)

Theis type curve matching ( $W(u,r/b)$ )

Recovery in a pumped well

Image well analysis

### Time-Drawdown

The time-drawdown analysis is based on a modified version of the Theis equation developed by Cooper and Jacob (1946). This method can be used for large values of time, or small values of pumping-to-monitoring well distance. At time  $t_1$ , we have

$$s_1 = 2.3Q/4\pi T * \log(2.25Tt_1/r^2S) \quad (1)$$

At time  $t_2$ ,

$$s_2 = 2.3Q/4\pi T * \log(2.25Tt_2/r^2S) \quad (2)$$

Subtracting (1) from (2),

$$s_2 - s_1 = 2.3Q/4\pi T * \log(t_2/t_1) \quad (3)$$

For  $t_1, t_2$  one log cycle apart,

$$ds = 2.3Q/4\pi T \quad (4)$$

where  $Q$  = discharge

$T$  = transmissivity

$ds$  = drawdown per log cycle time.

Choosing  $s = 0$  from (1) yields

$$S = 2.25Tt_0/r^2$$

where  $S$  = storativity

$T$  = transmissivity

$t_0$  = time at which drawdown is zero.

$t_0$  is determined graphically as the point where a line drawn through a semilog plot of time and drawdown data intersects the zero drawdown line. Figure 5 is such a plot constructed from data from wells MP-215-BR and 12-3A. Two lines are drawn due to a boundary-induced deflection. Results of the time-drawdown analysis:

MP-215-BR - radius 52.6 feet

Before deflection

Transmissivity	13,005 gpd/ft
Storativity	0.0005

After deflection

Transmissivity	7321 gpd/ft
Storativity	0.001

12-3A - radius 188.2 feet

Before deflection

Transmissivity	7907 gpd/ft
Storativity	0.0007

After deflection

Transmissivity	4821 gpd/ft
Storativity	0.0007

### Distance-Drawdown

This method is similar to time-drawdown. Modification of the Theis equation (Cooper and Jacob, 1946) gives

$$ds = 2.3Q/2\pi T$$

and



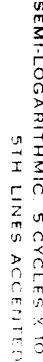


Figure 5. Plot of Time-Drawdown Data.

$$S = 2.25Tt/r_0^2$$

where  $r_0$  is determined graphically.

Figure 6 is a plot of distance and drawdown data for wells P-30, 11-9, 11-11, 12-3A, 13-12, and MP-215-BR. The black line marked (1) matches the most points; the black line (2) is a best fit. Both lines are a time  $t = 4140$  minutes. The red line is a best fit at  $t = 165$  minutes. Results are as follows:

Time = 165 minutes		
Transmissivity	10,137	gpd/ft
Storativity	0.0003	
Time = 4140 minutes		
Transmissivity	11,105	gpd/ft (1)
	9,280	gpd/ft (2)
Storativity	0.008	(1)
	0.005	(2)

### Theis Type Curve Matching

The Theis equation

$$h_0 - h = s = \frac{Q}{4\pi T} \int_0^\infty \frac{e^{-z}}{z} dz \quad (1)$$

$$r^2(s)/4Tt$$

can be written as

$$s = (Q/4\pi T)W(u) \quad (2)$$

$$\text{with } u = r^2(s)/4Tt \quad (3)$$

where  $W(u)$  is termed the well function of  $u$ .

A graph of  $W(u)$  vs.  $1/u$  (Figure 7), known as a type curve, is superimposed over time-drawdown data plotted on log-log paper.

The curves are matched to produce a best fit of the type curve

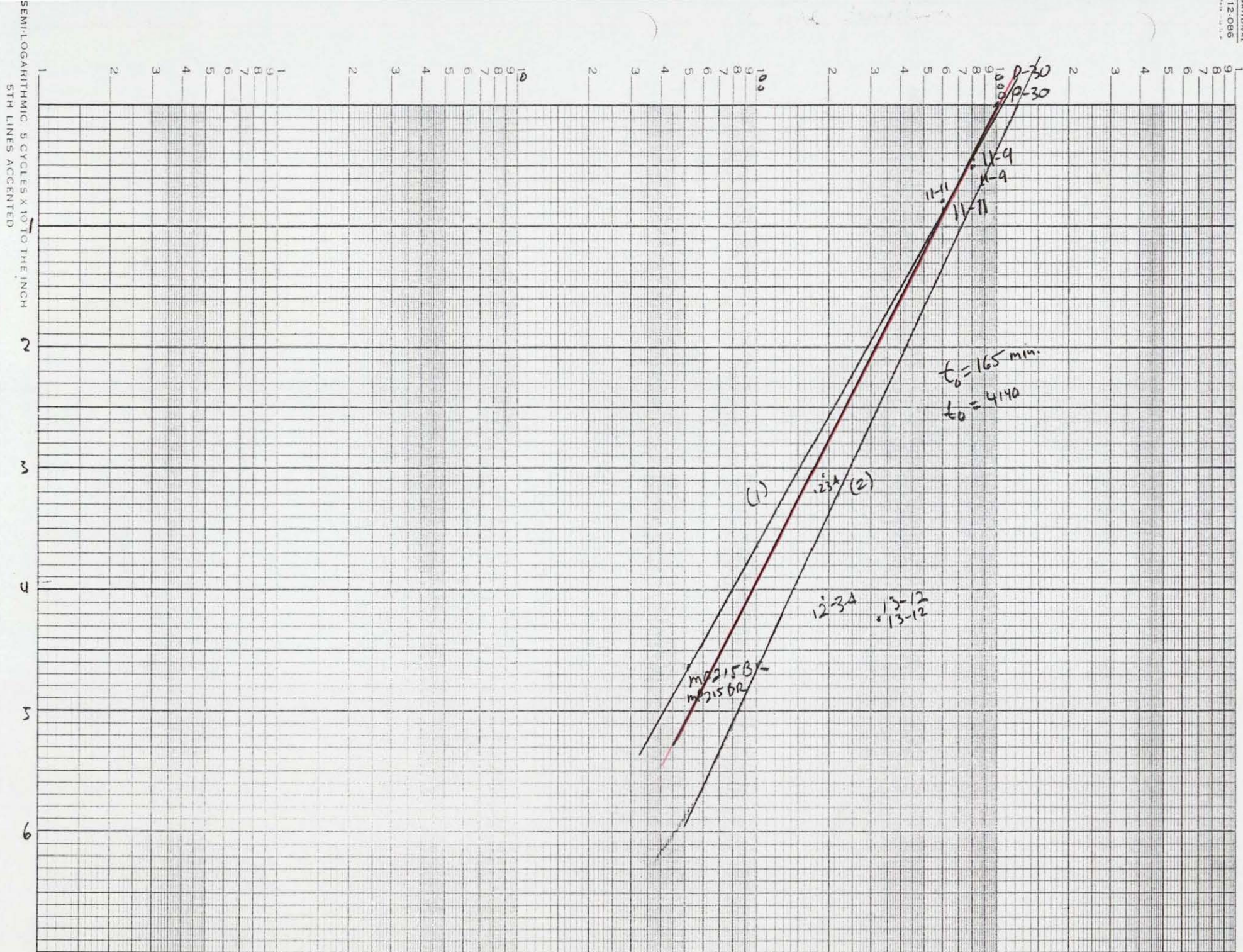


Figure 6. Plot of Distance-Drawdown Data.



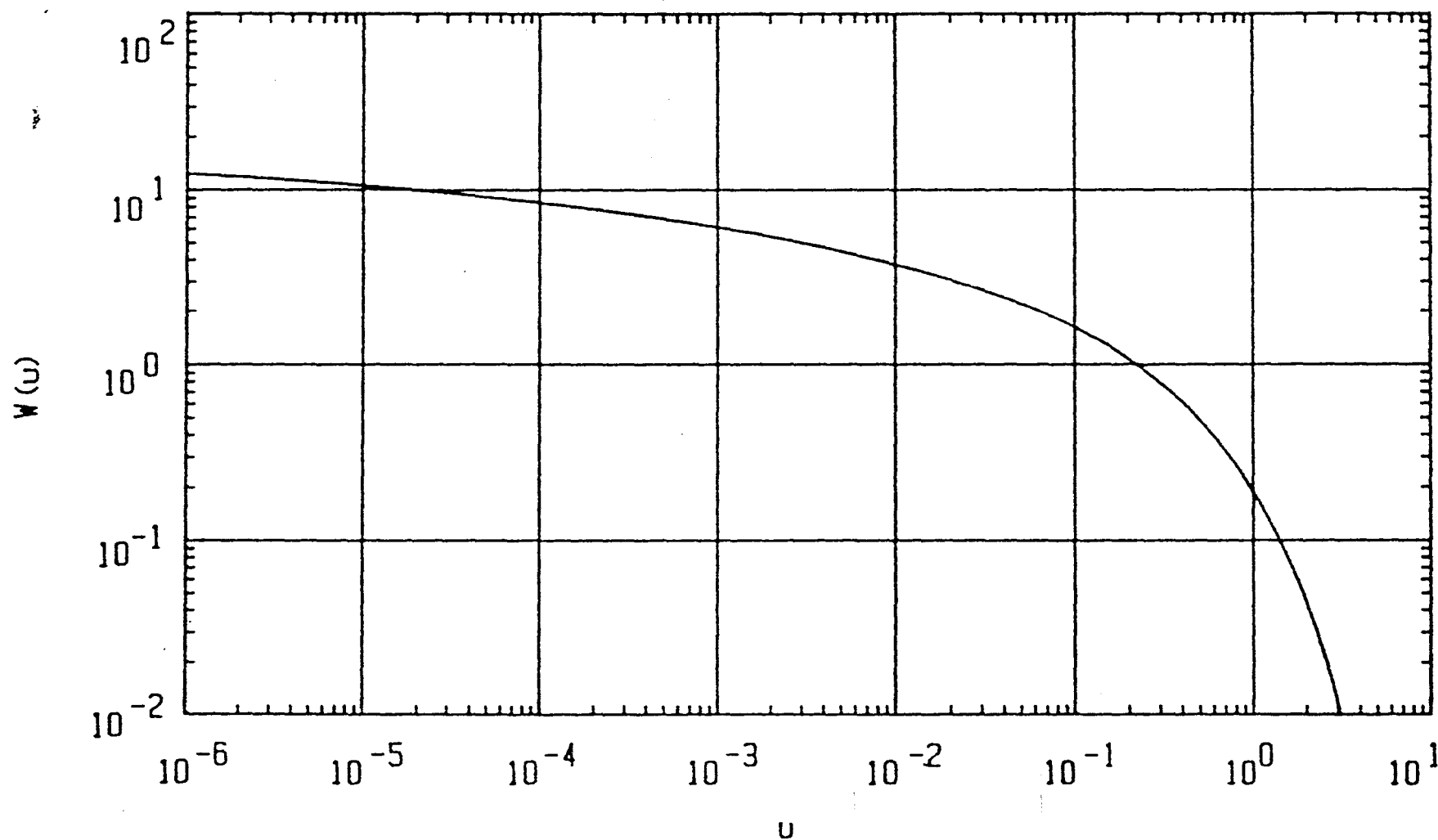


Figure 7.  $W(u)$  vs.  $u$  Type Curve. From Walton, 1987.

onto the data. Time and drawdown are read from a match point, usually chosen so that  $W(u) = 1/u = 1$ . These values are substituted into equations (2) and (3) to yield transmissivity and storativity values.

Inspection of the data from wells MP-215-BR and 12-3A (Figure 8), reveals a deflection in the curve, indicating leakage. In this situation a modified type curve, introduced by Hantush and Jacob (1955), is used (Figure 9). This curve is a plot of  $W(u, r/b)$  vs.  $1/u$ , where  $b$  is the saturated thickness of the aquifer. The curve-matching procedure is the same as for non-leaky aquifers, and transmissivity and storativity are calculated as

$$T = (Q/4\pi(s)) * W(u, r/b)$$

and

$$S = 4uTt/r^2$$

Again, the match point is chosen so that  $W(u, r/b) = 1/u = 1$ .

Results of this analysis:

Well	MP-215-BR	12-3A
Transmissivity	4297 gpd/ft	3306 gpd/ft
Storativity	0.002	0.0009

Recovery in a Pumped Well

Figure 10 is a plot of drawdown during pumping, and recovery after the pump has been shut off. Residual drawdown is expressed as

$$h_0 - h' = ds' = (2.3Q/4\pi T) (\log(2.25Tt/r^2S) - \log(2.25Tt/r^2S))$$

where  $h_0$  = original head

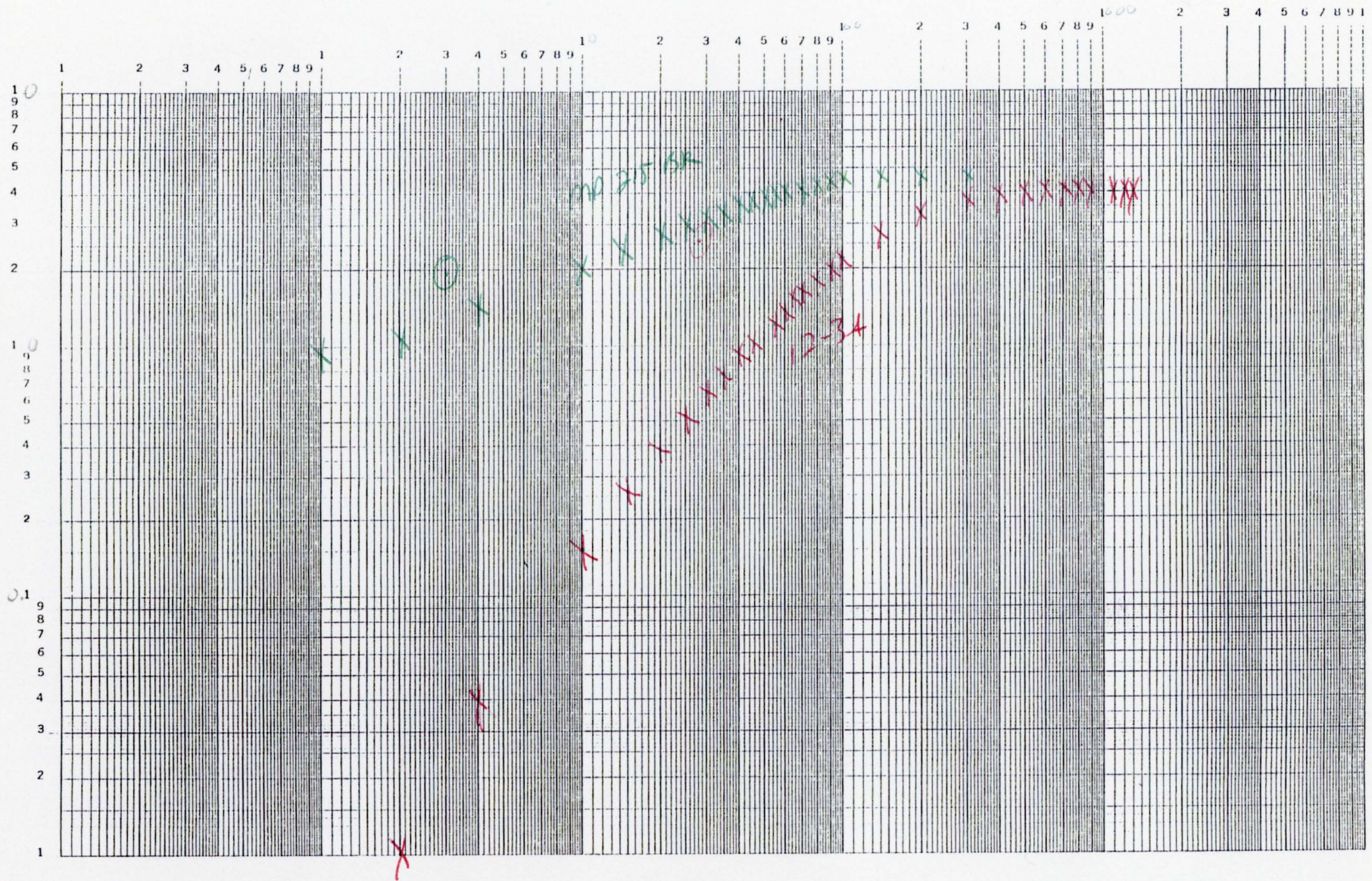


Figure 8 Log-log Plot of Time-Drawdown Data

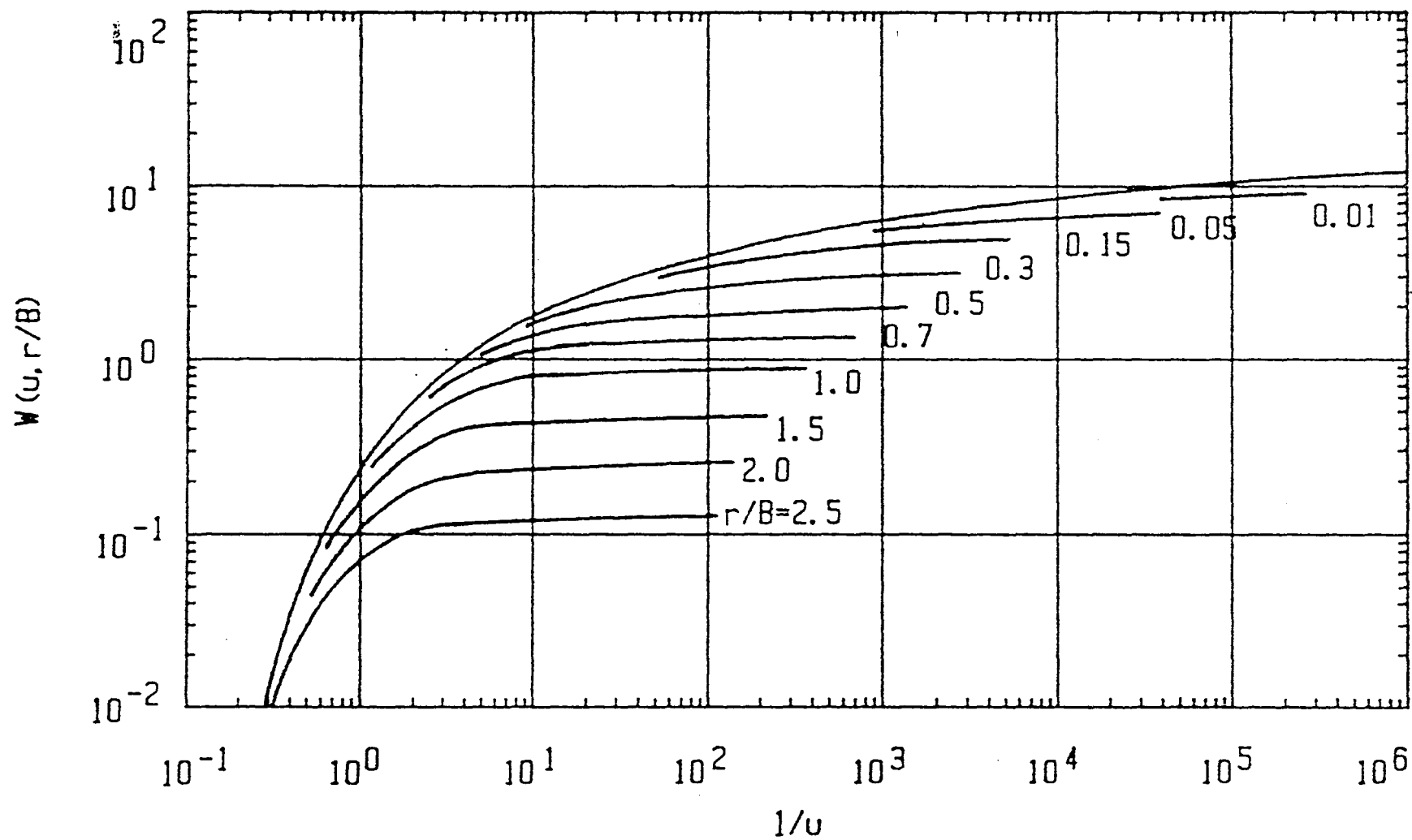


Figure 9.  $W(u, r/b)$  vs.  $1/u$ . From Walton, 1987.



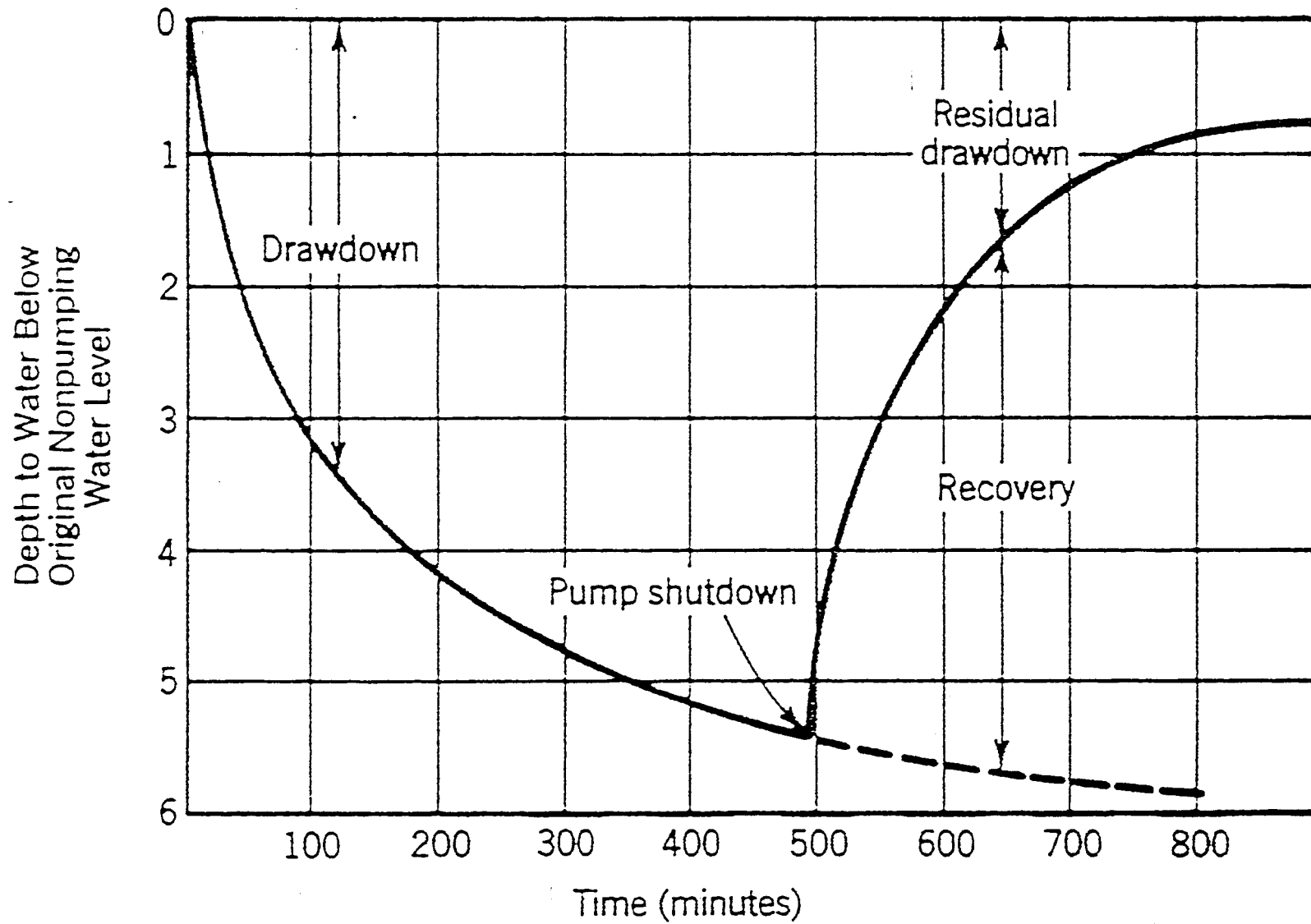


Figure 10. Plot of Drawdown and Recovery Curve vs. Time.  
From Domenico and Schwartz, 1990.



$h' =$  recovered head

$ds' =$  residual drawdown

$t =$  time since pumping started

$t' =$  time since pumping stopped.

This equation reduces to

$$ds' = 2.3Q/4\pi T * \log(t/t').$$

For calculations over one log cycle time,

$$ds' = 2.3Q/4\pi T$$

where  $ds'$  is the residual drawdown per log cycle.

From the data supplied by the 13-PW recovery test, for  $t' = 480$  minutes and  $t = 4802$  minutes, we have  $ds' = 2.65$  feet.

Therefore,

$$T = 2.3(13,500\text{ft}^3)$$

$$= 932.4\text{ft}^2/\text{day}$$

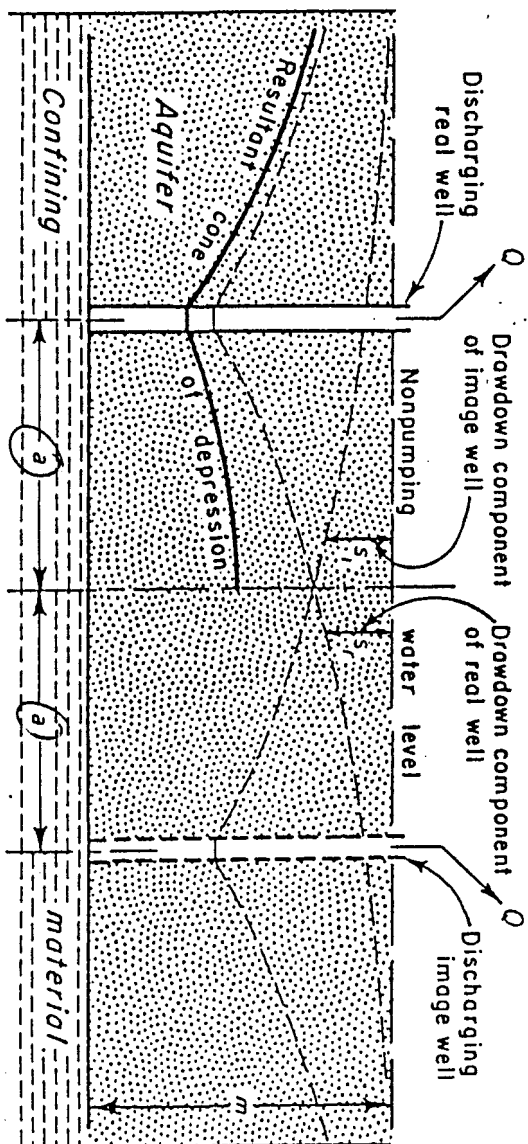
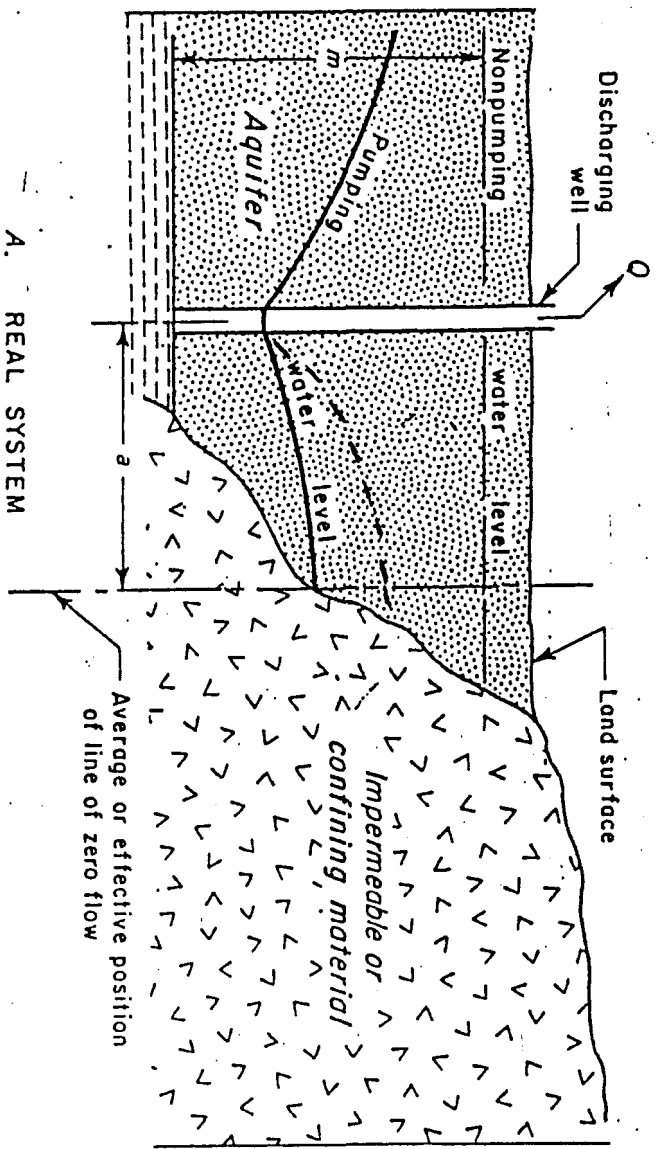
$$= 7459 \text{ gpd/ft.}$$

#### Image Well Analysis

All of the previous methods have assumed that the aquifer is infinite in areal extent. This procedure does not account for the presence of lateral boundaries in the Channel Sand.

Image well theory, in brief, states that an impermeable boundary acts to increase drawdown in an observation well.

Drawdown is affected as though there was another pumping well on the other side of the boundary, at a distance from the boundary equal to the distance from the boundary to the real well (Figure 11). Figure 12 shows the image well created by the Channel Sand boundaries. Note that each image well (I1A,I2A) creates its own image well (I1B,I2B).



NOTE:  
Aquifer thickness  $m$  should be very large compared to resultant drawdown near real well

### B. HYDRAULIC COUNTERPART OF REAL SYSTEM

Figure 11. Simplified Illustration of Image Well Theory.

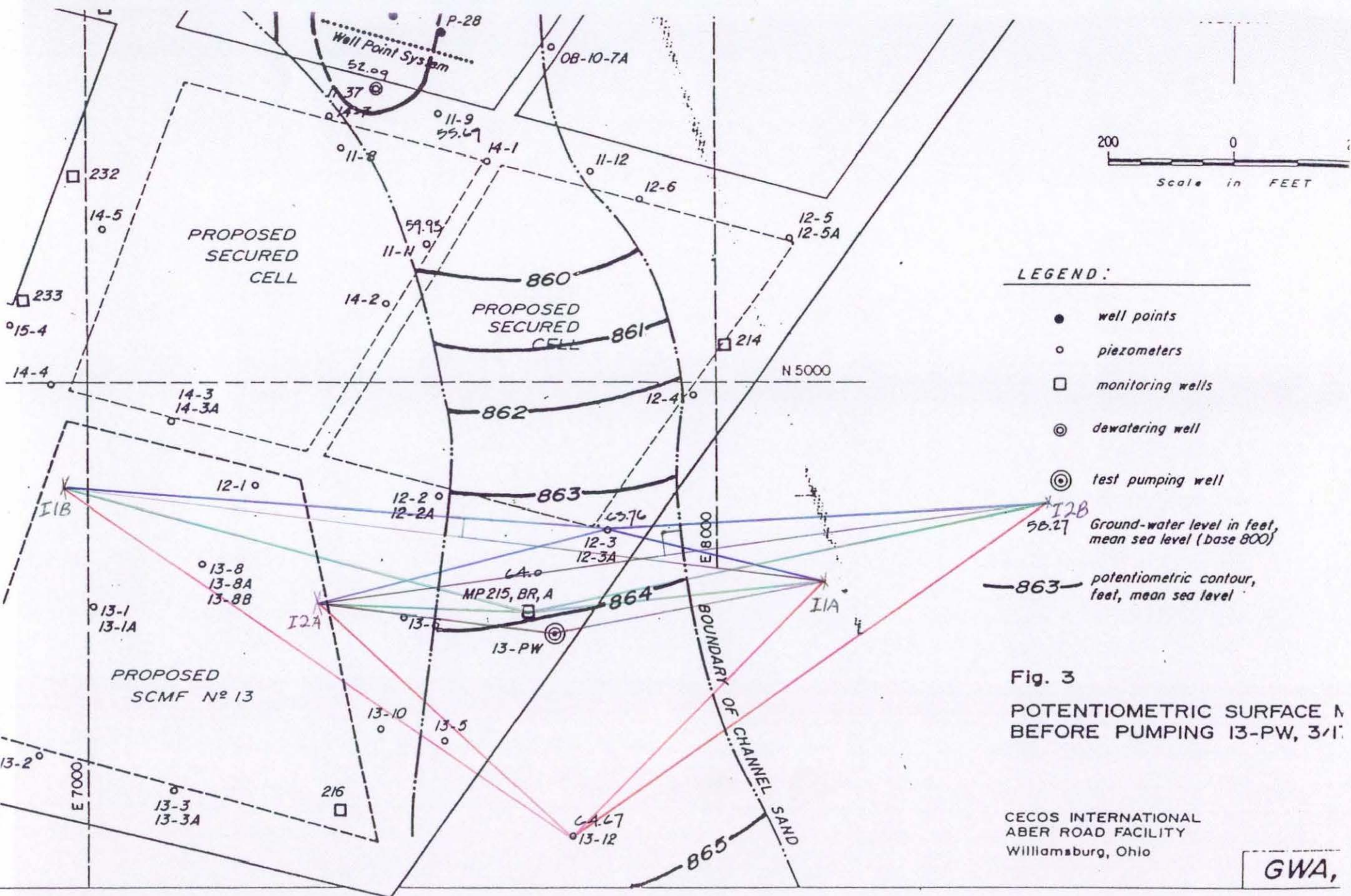


Figure 12. Image Wells Created by Channel Sand Boundaries. Adapted From GWA, 1987.

For this analysis, time-drawdown data and distance to image wells from 13-12, MP-215-BR, and 12-3A were used as follows: For each observation well, a value of  $u = r^2(S)/4Tt$  was calculated, using a storativity value of 0.0005 (GWA 1987), and two transmissivity values (10,000 and 20,000 gpd/ft). Walton (1987) provides a table to derive values of  $W(u)$  from  $u$ . These were substituted to yield

$$s = Q/4\pi T(W(u)(13-PW) + W(u)(I1A) + W(u)(I2A) + W(u)(I1B) + W(u)(I2B)).$$

Calculated drawdown  $s$  was compared with actual values taken from the In-Situ data.

Well	Calculated s	Actual s	Aquifer thickness
13-12	1.25, 1.25	3.15	18 ft.
12-3A	4.60, 2.73	1.64	32 ft.
MP-325-BR	4.84, 3.31	3.79	24 ft.

For MP-215-BR, a transmissivity value of 15,500 gpd/ft resulted in a drawdown of 3.80 feet.

## Summary of Results

Analysis	Transmissivity(gpd/ft)	Storativity
Time-Drawdown	4821 - 13,005	0.0047 - 0.001
Distance-Drawdown	10,137 - 11,105	0.005 - 0.0078
Type Curve	3306 - 4297	0.0009 - 0.0016
Recovery-Drawdown	7459	NA
Image Well	15,500	0.0005 assumed

## Comments

Several assumptions are incorporated into the use of the Theis equation and its various incarnations:

- 1) The aquifer is infinite, homogeneous, flat lying, and has a constant thickness.
- 2) The pumping and observation wells are fully penetrating.
- 3) An infinite amount of water is stored in the aquifer.

In the case of the Channel Sand, we have a finite body that varies in thickness and slope. The presence of a boundary or boundaries is indicated on the plots of time-drawdown data in Figures 5 and 8. Figure 13 is cited by Walton (1987) as a case involving a confined, bounded aquifer. We can see two upward deflections at 12 and 70 minutes, indicating the presence of two boundaries. In this case, data before and after the deflection was analyzed. That procedure has been followed here for time-drawdown and distance-drawdown analyses, resulting in two sets of data for each well.

The impact of variability in slope and thickness is evident in the image well analysis. Well 12-3A is downslope from 13-PW, and

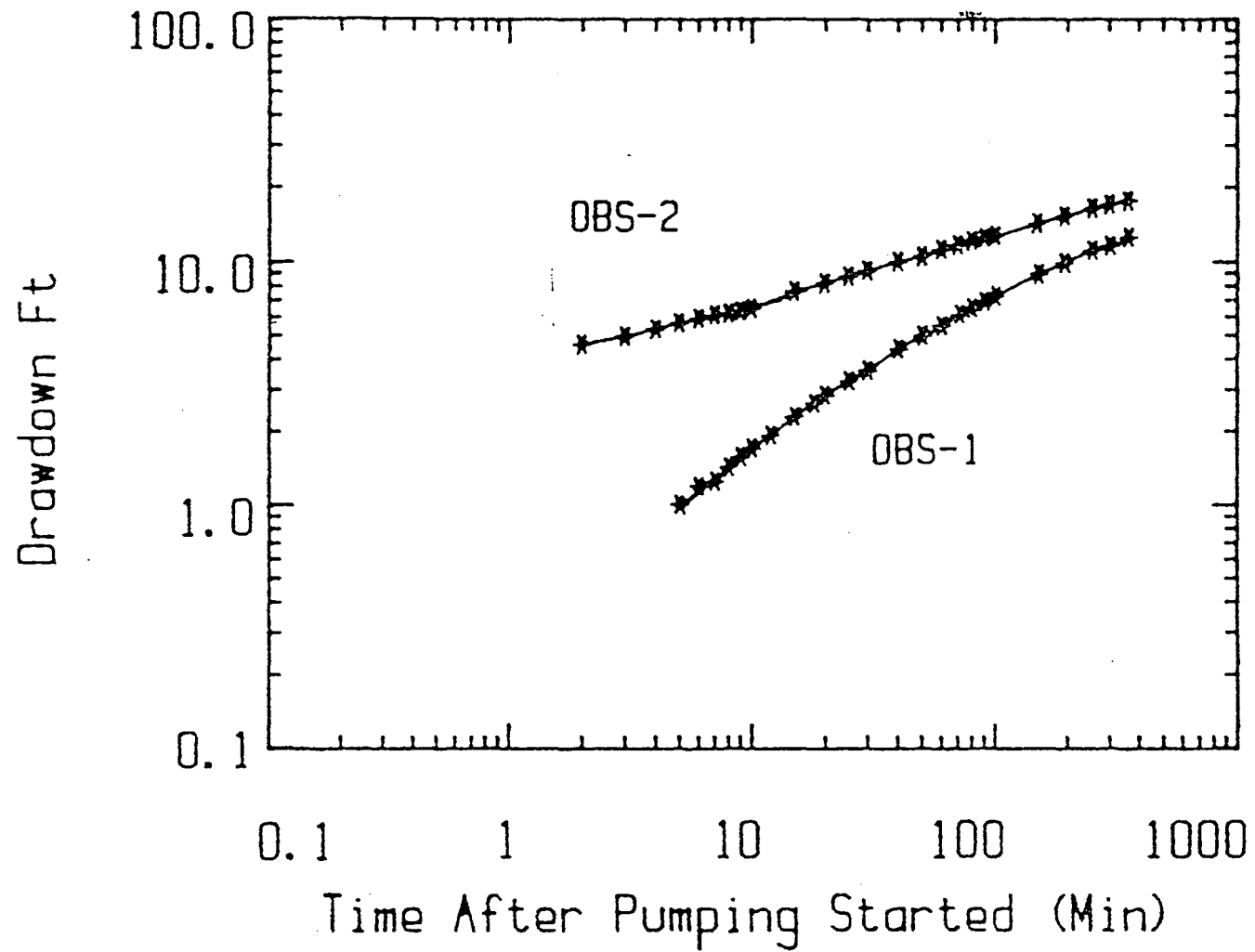


Figure 13. Time-Drawdown Plot With Deflections. From Walton, 1987.

is in a thicker part of the aquifer (S&ME, 1987). Both of these conditions could be expected to lessen drawdown. S&ME data also indicate thinning of the aquifer toward 13-12, which may increase drawdown observed at that well.

Examination of well log data (S&ME, 1987) reveals that well 12-3A is screened in a 1.5 ft. thick gravel seam. This seam could act as a high-conductivity conduit, replenishing water and attenuating local drawdown. Well 13-12 is screened in finer grained material than 12-3A, which may add to drawdown differences between the two wells. MP-215-BR is screened in poorly graded sand with silt; its well log does not indicate the presence of heterogeneities.

Information from GWA (1987) indicates that all of the wells mentioned in this paper are partially penetrating (not screened to full aquifer thickness). The effects of partial penetration are to introduce vertical flow components around the pumping well, which may affect drawdown at observation wells. If a well is at a distance

$$r > 1.5m(K/K')^{0.5}$$

from the pumped well, where

$m$  = aquifer thickness

$K$  = horizontal conductivity

$K'$  = vertical conductivity,

then the effects of partial penetration can be ignored. If  $K$  and  $K'$  are of the same order of magnitude, then the condition  $r > 1.5m$  is sufficient (Domenico and Schwartz, 1990). The Channel Sand around MP-215-BR appears to be relatively homogeneous and

isotropic, without significant horizontal heterogeneities, so we have

52.6 feet > 1.5(24 feet).

Other wells are also sufficiently distant from 13-PW.

The GWA report notes that water levels were drawn down below the top of the aquifer during the 13-PW test. This may account for reduced transmissivity and increased storativity values. The log-log data from Figure 8 do not reflect this. No attempt was made to match a  $W(u_a, u_b, \eta)$  type curve to the data. It should be noted that the effect of dewatering is to raise storativity levels, perhaps by a few orders of magnitude.

## Conclusion

Based on the data generated and the above discussion, the Channel Sand has a transmissivity of 10,000 to 15,000 gpd/ft, and a storativity on the order of 10<sup>-4</sup>, probably between 0.0003 and 0.0007. Low values of transmissivity (less than 8000 gpd/ft) are incorrect due to the effects of dewatering and other violations of assumptions made in implementing the Theis equation and its variations. As expected, variability in thickness and lithology affects values of transmissivity. Storativity values are raised by dewatering. The presence of boundaries should be accounted for in analysis of small-body aquifers. Careful evaluation of local hydrogeology is essential for proper interpretation of aquifer test data.



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# Time-Drawdown Data

Well 12-3A			Well MP-215-BR		
Time(minutes)	Drawdown(feet)		Time	Drawdown	
1	0		1	0.95	
2	0.01		2	1.10	
4	0.04		4	1.40	
10	0.15		10	2.00	
15	0.26		15	2.38	
20	0.38		20	2.71	
25	0.52		25	2.95	
30	0.64		30	3.18	
35	0.78		35	3.35	
40	0.91		40	3.53	
45	1.04		45	3.66	
50	1.15		50	3.79	
55	1.28		55	3.90	
60	1.40		60	3.99	
65	1.52		70	4.16	
70	1.62		80	4.30	
80	1.82		90	4.42	
90	2.02		100	4.55	
100	2.20		140	4.63	
140	2.80		200	4.64	
200	3.33		300	4.64	
300	3.76		400	4.63	
400	3.94		500	4.61	
500	4.01		600	4.66	
600	4.05		700	4.66	
700	4.08		800	4.63	
800	4.09		900	4.63	
900	4.10		1000	4.63	
1000	4.08				

## Distance-Drawdown Data

Well			time = 165 min			time = 4140 min		
	Drawdown		Distance			Drawdown	Distance	
MP-215-BR	4.63		52.6			4.64	52.6	
13-12	4.23		327.9			4.26	327.9	
12-3A	3.05		188.2			4.06	188.2	
11-15	0.01		1287.0			0.02	1287.0	
11-9	0.05		810.0			0.45	810.0	
11-11	0.08		610.0			0.86	610.0	
P-30	0.00		1000.0			0.01	1000.0	

## Image Well Radii

Well	Distance to:						
13-12	13-PW	I1A	I1B	I2A	I2B		
12-3A	327.9	575.0	908.0	555.0	935.0		
MP-215-BR	188.2	360.0	870.0	477.0	709.0		
	52.6	480.0	768.0	337.0	855.0		